

On the scarcity of Magellanic Cloud-like satellites

Phil A. James^{*} and Clare F. Ivory^{*}

Liverpool John Moores University, Birkenhead, CH41 1LD, UK

Accepted . Received ; in original form

ABSTRACT

We have used $H\alpha$ narrow-band imaging to search for star-forming satellite galaxies around 143 luminous spiral galaxies, with the goal of quantifying the frequency of occurrence of satellites resembling the Magellanic Clouds, around galaxies comparable to the Milky Way. For two-thirds of the central galaxies, no star-forming satellites are found, down to luminosities and star-formation rates well below those of the Magellanic Clouds. A total of 62 satellites is found, associated with 47 of the central galaxies searched. The R -band magnitude difference between central galaxies and their satellites has a median value of 4.6 mag, and a maximum of 10.2 mag. The mean projected separation of the satellites from their central galaxies is 81 kpc, or 98 kpc for systems beyond 30 Mpc. Thus star-forming satellites are quite rare, and the Milky Way is unusual both for the luminosity and the proximity of its two brightest satellites. We also find that the Clouds themselves are unusual in that they appear to form a bound binary pair; such close satellite pairs, of any luminosity, are also extremely rare in our survey.

Key words: galaxies: spiral – Magellanic Clouds – galaxies: groups: general.

1 INTRODUCTION

Satellite galaxies have attracted an enormous amount of observational and theoretical study over the past decade. This is partly a consequence of the hierarchical nature of galaxy formation in the currently-popular Λ CDM models, within which some or all dwarf satellites may represent left-over building blocks from an earlier assembly phase of large galaxies. These models also suffer from the so-called ‘substructure problem’ (Klypin et al. 1999; Moore et al. 1999), in that the predicted numbers of low-mass dark matter haloes are far larger than the observed numbers of low-luminosity galaxies that might naturally be expected to occupy them. The problem has been addressed in the latest models (Benson et al. 2002; Simon & Geha 2007; Koposov et al. 2009) by decreasing or completely suppressing the star-formation (SF) efficiency in low mass haloes. One great success of these models was that they predicted the existence of ultra-low mass dwarf galaxies substantially fainter than the canonical dwarf spheroidals. These ultra-faint dwarfs were subsequently discovered, primarily through searches of data from the Sloan Digital Sky Survey (SDSS) (Willman et al. 2005; Koposov et al. 2007; Walsh et al. 2007).

Satellites are also potentially of importance in other ar-

eas of galaxy physics. Merging of low-mass satellites with their central hosts (minor mergers) is one route for the formation of thick disk components, and for building bulges. For example, Domínguez-Palmero & Balcells (2008) cite repeated minor merger episodes as their preferred mechanism through which bulges can grow without destroying the surrounding disk, thus preserving the strong correlation between disk and bulge colours within individual galaxies found by these authors. Another important problem concerns the continued gas supply to large disk galaxies, first noted by Larson et al. (1980). These authors estimate that the Milky Way (MW) will consume the current disk gas reservoir in ~ 2 Gyr, and that the equivalent timescale for 36 external galaxies is little longer, with a mean of 3.9 Gyr, and certainly less than a Hubble time. This points clearly to the need for continued gas supply to support ongoing SF in most or all spiral galaxies. Such continued or even increasing supply is also indicated by the K-dwarf metallicity distribution in the MW, investigated by Casuso & Beckman (2004), who also conclude that the ‘burstiness’ apparent in the SF history of the MW may indicate significant gas accretion events. However, Grcevich & Putman (2009) estimate the total gas mass in the current populations of satellites around the MW and M31 (not including the Magellanic Clouds), finding a total of only $1 - 2 \times 10^8 M_{\odot}$ for the MW. They conclude that this is too little to provide a satisfactory explanation of the deficiency of low-metallicity dwarf stars in the Galactic disk (the ‘G-dwarf problem’), which requires a

^{*} E-mail: paj@astro.livjm.ac.uk (PAJ); cfi@astro.livjm.ac.uk (CFI)

continued supply at an average rate of $\sim 1 \text{ M}_\odot \text{ yr}^{-1}$ over a period of 5-7 Gyr.

Much of the recent interest in satellites has concentrated on extremely low-luminosity dwarf galaxies, which in general can only be studied within the Local Group. However, the more massive satellites are also of substantial importance. In this paper we focus on satellites that are near analogues of the two most luminous objects around the MW, the Large and Small Magellanic Clouds (LMC and SMC, collectively MC, henceforth) which are characterised by quite high masses and luminosities (much higher at least than any other galaxies within several hundred kpc of the Milky Way), ongoing SF indicating substantial gas reservoirs, and their nearness to us (50 and 60 kpc for the LMC and SMC respectively). They also appear to be close to one another, probably forming a bound pair, with an interaction history that may be of great importance, both for their SF histories and for the origin of the Magellanic Stream of H I gas.

For comparison with the satellite galaxies found in the present study, we assume *R*-band luminosities of 1.6×10^9 and $3.7 \times 10^8 \text{ L}_\odot$, and SF rates of 0.17 and $0.027 \text{ M}_\odot \text{ yr}^{-1}$ for the LMC and SMC respectively. The latter are derived from the H α photometry of Kennicutt & Hodge (1986) with magnitude-dependent extinction corrections derived following Helmboldt et al. (2004). Again for comparison purposes, we adopt an *R*-band luminosity for the Milky Way of $1.5 \times 10^{10} \text{ L}_\odot$; thus to a distant observer, the Milky Way would appear 9.4 times more luminous than the LMC, a difference of 2.43 mag.; and 40.5 times more luminous than the SMC, a difference of 4.02 mag.

One reason for looking for satellites like the LMC and SMC lies in the recent simulations, discussed above in the context of ultra-faint dwarfs. While these models have had great success in accounting for the luminosity function of low-mass satellites ($10^4 - 10^8 \text{ L}_\odot$), most fail to predict the existence of satellites resembling the Magellanic Clouds in any significant numbers. For example, Benson et al. (2002) find satellites as massive as the LMC in fewer than 5% of simulated haloes that harbour MW-like central galaxies. Simon & Geha (2007) also find that their models, which rely on reionization to truncate SF in satellite haloes, accurately explain the numbers of faint satellites but again do not predict MC-like satellites. Okamoto et al. (2010) confirm that the underprediction of the numbers of the brightest satellites for MW-like systems occurs even in the most recent Λ CDM simulations.

Λ CDM simulations of the satellite populations of MW-like galaxies by Koposov et al. (2009) also fail to match the observed luminosity function of Local Group satellites in their brightest bin, which comprises the LMC and SMC. As a result these authors introduce additional models with parameters tuned to allow the production of MC-like satellites. Similarly, Kravtsov (2010) recently produced models of MW-like haloes where the whole SF efficiency model is tuned to produce SMC- and LMC-like satellites.

Boylan-Kolchin et al. (2009) analyse the statistical properties of haloes likely to host MW-like galaxies in the Millennium-II Λ CDM simulation, and determine the probability of hosting a satellite as massive as the LMC to be 8-25%, depending on the mass adopted for the MW halo (larger masses corresponding to higher probabilities). Similarly, they find the probabilities of having a second satellite

as massive as the SMC to be in the range 3.3-20%. They argue from this analysis that the existence of the LMC and SMC favours the higher end of the MW halo mass range. However, higher mass favours more recent and substantial mergers in the past history, making the survival of the MW thin disk harder to understand. This raises obvious questions about how typical the Magellanic Clouds are.

As one counter-example to the above studies, Libeskind et al. (2007) and Zavala et al. (2008) presented disk galaxy *N*-body/SPH simulations which *do* predict the existence of massive satellites resembling the Magellanic Clouds, which they take as confirmation of the validity of their models. Again, the strength of this argument depends on whether the MW system is a special case in this respect.

Magellanic Cloud-like satellites are also important because of their potentially significant impact on the growth of stellar mass in disk galaxies. Hopkins et al. (2008) present simulations of mergers of disk galaxies with ‘live’ (dynamically interacting) haloes, which show that MW-mass disks can survive mergers with satellites one-third of their mass while remaining recognisable disks, while mergers with satellites of the mass of the LMC have almost no effect, causing only some disk thickening. Even this effect is found to be negligible for satellites less than one-tenth of the central galaxy mass. Their models also predict a rapid, radial infall of satellites, almost regardless of their initial impact trajectory. However it is not clear whether this prediction is consistent with the multiply-wound satellite trails around some nearby galaxies, e.g. those around NGC 5907 found by Martínez-Delgado et al. (2008). Taffoni et al. (2003) present similar modelling, but they focus on the effect of mass loss from the satellite during the accretion process, which they find to have a substantial effect on dynamical friction timescales. Applying this to the LMC, they predict it is likely to merge with the MW on a ~ 4 Gyr timescale. Overall, these simulations show that mergers with MC-like satellites provide a plausible mechanism for the fast and efficient growth of disk galaxies, providing of course such satellites exist in significant numbers.

However, the assumption that our Galaxy is ‘typical’ in any sense, whilst frequently made, is very risky; this is a sample of one galaxy that may be unusual in some respects. An early test of this assumption was performed by Holmberg (1969) who searched for satellite galaxies around nearby field galaxies using Palomar Sky Atlas photographic plates. He found that bright satellite galaxies comparable to the MC are quite rare, at least within ~ 57 kpc projected distance from the central galaxies studied. This conclusion was supported by Lorrimer et al. (1994), who used higher-quality photographic material and concluded that a typical spiral central galaxy only has one satellite brighter than $M_B = -16.5$ within a projected separation of 375 kpc. Zaritsky et al. (1993) present a spectroscopic study of 62 nearby bright spiral galaxies, finding 69 confirmed satellites around 45 of these central galaxies. The 69 satellites have absolute *B* mags between -20 and -13 , with the bulk of the distribution between -18 and -14 . Nine of the 69 are as bright as or brighter than the LMC, with the SMC being close to the median luminosity.

Here we present a study that aims to build on these results, using narrow-band imaging to search for satellite galaxies around disk galaxies in the local Universe. In addi-

tion to these statistical goals, a strong motivation for this work is to identify the best analogues of the MC system, to provide a comparison sample for further studies of, for example, the origin of the Magellanic Stream.

Throughout the paper we assume a Hubble constant of $70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, although for the nearer galaxies we adopt distances corrected for Virgo Cluster infall only, taken from the NASA/IPAC Extragalactic Database (NED).

2 METHODS: SATELLITE DETECTION FROM $\text{H}\alpha$ IMAGING

2.1 Motivation for narrow-band imaging searches

The major problem in assembling catalogues of satellite galaxies is background or foreground interloper galaxies, which appear to be companions through line-of-sight projection. These can be statistically accounted for by subtracting counts from comparison fields, as was done by Holmberg (1969), but this is a highly uncertain procedure due to clustering, and the small ‘signal’ of true satellites. Multi-object spectroscopy is the most secure way to overcome this problem, but it is time consuming given that the input catalogues are heavily contaminated by background sources, and that satellites can be faint and of low surface brightness.

Many of these problems can be overcome by using narrow-band imaging, through a filter with a passband that includes a bright emission line ($\text{H}\alpha$ in the present paper) at the redshift of the central galaxy or galaxies targeted. This has the advantages that it can be used over wide fields given current large-format CCDs, each field requires just two observations (through the narrow-band $\text{H}\alpha$ filter, and a shorter exposure through a broader filter for continuum subtraction), and only sources with an emission line within the narrower filter passband will appear in the continuum-subtracted image, thus excluding almost all background and foreground galaxies due to the redshifting of the target emission line out of the passband of the filter. In addition, $\text{H}\alpha$ narrow-band imaging is highly sensitive to even low levels of star formation; HII regions tend to be clumpy and of high surface brightness, even in generally LSB galaxies.

The major limitation of this technique is that it only picks up the star-forming galaxies within the field, and has no sensitivity for quiescent galaxies such as most elliptical and dwarf elliptical types. However, the star-forming satellite galaxies are the most relevant ones if the goal is to identify potential sources of gas supply to central galaxies. It is important here to note the conclusion of recent papers (Meurer et al. 2006; James et al. 2008b), which find that almost all gas-rich galaxies in the local Universe form stars. Thus to a good approximation $\text{H}\alpha$ selection can be considered equivalent to selecting of galaxies with significant cold gas content, although we note some interesting (but apparently rare) cases of galaxies with high molecular gas contents which have very low SF rates, e.g. for the galaxies in Stephan’s Quintet (Appleton et al. 2006; Cluver et al. 2010).

2.2 Previous work

The methods used in the present paper were first tested using data from the $\text{H}\alpha$ GS survey (James et al. 2004), with results being presented in James et al. (2008c). We looked at continuum-subtracted narrow-band $\text{H}\alpha$ imaging for 119 central galaxies, finding a total of 9 probable star-forming satellites. The typical R -band luminosities and $\text{H}\alpha$ -derived SF rates of the 9 satellites were similar to those of the SMC, with the LMC being more luminous than all 9 and having a SF rate larger than 8 of the 9. No central galaxy was found to have more than one star-forming satellite. Thus the overall conclusion was that MC-like bright, star forming satellites seem to be uncommon. However, it is important to note some significant caveats with the results presented in James et al. (2008c). The CCD imaging used for $\text{H}\alpha$ GS had a relatively small areal coverage ($\sim 10'$ squared) so there are substantial incompleteness corrections. Also, the relatively small volume of the local Universe used to select the central galaxies, and the aim for complete sampling of dwarf galaxies, resulted in a restricted number of bright central galaxies. Thus, for example, only 31 of the central galaxies studied in James et al. (2008c) are brighter than $10^{10} L_{\odot}$ and can thus be considered truly comparable with the MW.

A potentially important additional consideration with the narrow-band imaging technique is that uncertainties in the continuum subtraction process can result in spurious objects which do not in fact have any line emission. Even for those objects where the line emission is real, the narrow-band imaging alone cannot rule out the possibility of it being another line, for example $[\text{OIII}]\lambda 5007 \text{ \AA}$ redshifted into the narrow-band filter passband. Finally, even if it is truly the $\text{H}\alpha$ line, the width of the narrow-band filters used here ($80 - 100 \text{ \AA}$) means that galaxies not truly associated with the central galaxy, separated by distances as large as 30 Mpc assuming pure Hubble expansion, may be included as potential satellites. However, spectroscopy of 13 of our candidate satellites (Ivory & James 2010) has confirmed that in every case, the emission revealed in the narrow-band imaging was truly $\text{H}\alpha$ emission, very close in recession velocity to that of the central galaxies (a maximum difference of 263 km s^{-1} , and a mean difference of only 116 km s^{-1}). Thus we have good confidence that virtually all of the sources discussed in the present paper are true satellites, genuinely associated with the central galaxies, with very small contamination by interlopers.

3 SAMPLE SELECTION AND DATA

3.1 Galaxy sample and observations

This study utilises the same methods as James et al. (2008c), but a completely independent dataset, with very different selection criteria. $\text{H}\alpha$ imaging was obtained for galaxies hosting recent core-collapse SNe, for a study of the environments immediately surrounding the locations of the SN (Anderson & James 2008) giving constraints on progenitor stars. Selection by core-collapse SN occurrence naturally weights the sample towards the brightest and most rapidly star-forming galaxies, making this an excellent complementary sample to that used in James et al. (2008c).

The overall galaxy sample is listed in

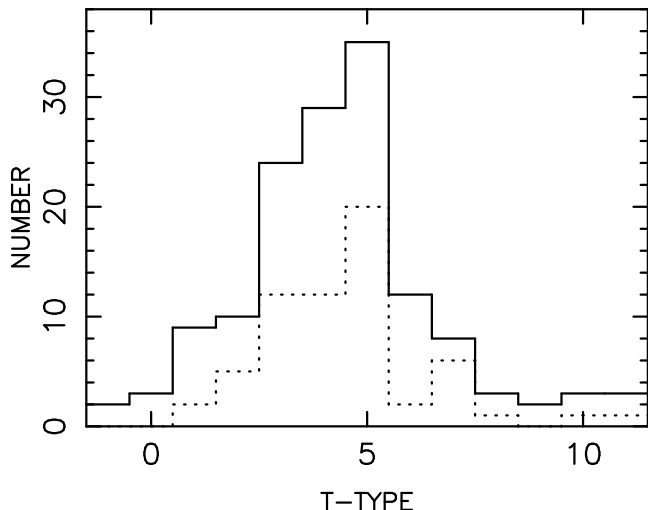


Figure 1. Histogram showing the range of Hubble T -types of central galaxies searched for satellites (solid line); and the numbers of satellites found, separated by the T -types of their central galaxies.

Anderson & James (2008), and so we do not go into detail here on the sample selection or data reduction. We use all data taken with the Wide Field Camera (WFC) on the Isaac Newton Telescope using either filter number 197 ($H\alpha$, central wavelength 6568 Å) or 227 (redshifted $H\alpha$, central wavelength 6657 Å), where the numbers are from the Isaac Newton Group filter database. These filters cover all recession velocities from 0 - 6100 km s⁻¹, with a transition point between the two of ~ 2400 km s⁻¹. We do not include galaxies from the sample of Anderson & James (2008) that were observed using the [SII] filter centred on 6725 Å (which are too distant for unambiguous detection of faint satellites) or those observed with the Liverpool Telescope (where the field of view of the CCD camera is too small for an efficient satellite search).

The remaining dataset of wide-field $H\alpha$ and R -band imaging, that was used to search for star-forming satellites, comprised 143 disk galaxies, with a distribution of Hubble T -types that is given in Table 1 and shown as the solid line in Fig. 1. A small number of galaxies with no specific type classifications in NED were classified by the first author, based on our own R -band images. Selection by core-collapse supernova occurrence weights the sample strongly towards bright, star-forming spirals of types Sb - Scd; these constitute 70% of the current sample (100/143). This closely matches the 66% contribution of galaxies of these types to the total star-formation density of the local Universe, as found by James et al. (2008a), and thus this appears to be a representative sample of star-forming galaxies at the present epoch.

3.2 Data reduction

All CCD images used for the satellite detection were bias and dark subtracted, flat fielded using twilight sky flats, and continuum subtracted, all using standard procedures as outlined in Anderson & James (2008). Given the passband of the filters used, it should be noted that throughout this paper, ' $H\alpha$ ' in fact refers to both $H\alpha$ and [NII] 6548 & 6584 Å

emission; no attempt is made to correct for the latter. The satellite search was done by eye, scanning the continuum-subtracted $H\alpha$ images for clear emission-line objects, and 'blinking' such objects with the spatially-registered R -band images to confirm that there was a coincident source with detectable emission in the broader filter (noting that the latter includes $H\alpha$). The scanning of images for satellites was done independently by both authors. Thus for the present paper, a 'satellite' is an object with emission in both images, that is separated from the main body of the central galaxy. Given the aims of the present paper, any companions with an R -band luminosity more than one-third of that of the central galaxy were not included in our analysis or statistics. However, it is important to bear in mind that there is no universal definition of 'satellite' when comparing different studies, many of which do include such bright companion galaxies. Only the central CCD (number 4) of the WFC 4-chip array was used for the satellite search, to avoid complications caused by the gaps between the CCDs, and vignetting losses affecting the outer corners of the array. The area of the single CCD is $\sim 12' \times 24'$, corresponding to 111×221 kpc at the median distance (31.7 Mpc, 2220 km s⁻¹) of the galaxies searched in this study, or $> 190 \times 379$ kpc for the galaxies in the upper quartile of distance. Thus incompleteness is very small for satellites as close to their central galaxies as are the Magellanic Clouds to the Milky Way (50 & 60 kpc), but a significant fraction of satellites at the virial radii of the host systems (typically 200 - 300 kpc) will be missed.

This incompleteness can be quantified to some extent using the method outlined in James et al. (2008c). Briefly, this involves calculating the fraction of a circular volume centred on each of the central galaxies that would be visible, with the 'invisible' regions being both those lying off the CCD, and those projected onto the disk of the central galaxy. These fractions can then be summed for the whole sample and divided by the number of central galaxies to give an estimated completeness fraction, under the assumption of uniformly distributed satellites. This was first done for the present sample using the 'Magellanic radius' defined in James et al. (2008c); this is the radius (76 kpc) corresponding to a sphere with twice the volume necessary to include both Magellanic Clouds. Overall, we sample about 75% of this volume for the 143 galaxies in the current sample, with the most substantial loss being for galaxies closer than 20 Mpc. Beyond 30 Mpc, we see the full volume out to the Magellanic Radius, apart from the cylinder comprising about 5% of the total volume that is projected against the central galaxy disk. For greater central-satellite separations, the incompleteness obviously becomes larger; repeating the above calculation for a radius of 200 kpc, we find that we can only see 34% of the corresponding volume. However, the Λ CDM models of Koposov et al. (2007) predict that only a very small fraction of satellites lies as far out as 200 kpc, and that between 70 and 90% (depending on the model parameters used) lie within 100 kpc of the simulated central galaxy. Our survey efficiency for a 100 kpc radius sphere is 64%. Overall, we conclude that we should pick up about 50% of all satellites, and 75% of those within the 'Magellanic radius'.

Table 1. The Hubble T -type distribution of the parent sample and satellite-hosting samples.

T -type Classn.	<0	0	1	2	3	4	5	6	7	8	9	10	Other	
	S0	S0a	Sa	Sab	Sb	Sbc	Sc	Scd	Sd	Sdm	Sm	Im	S, Pec etc	All
N_{CENT} tot	2	3	9	10	24	29	35	12	8	3	2	3	3	143
N_{CENT} sat	0	0	2	4	8	12	12	1	5	1	0	1	1	47
N_{SAT}	0	0	2	5	12	12	20	2	6	1	0	1	1	62

4 RESULTS OF THE SATELLITE SEARCH

The main results of the satellite search are summarised in Table 1. The total number of central galaxies searched was 143, approximately one-third of which were found to have at least one associated line-emitting galaxy. Of these 47 central hosts, 37 have only a single satellite, 7 have two satellites, 2 have three satellites and one (NGC 3074) has five satellites; thus the 47 central galaxies host a total of 62 satellites. The T -types of the central galaxies for each of the 62 is shown as the dotted line in Fig. 1; this matches the type distribution for all galaxies searched within statistical uncertainties, i.e. there is no evidence for any galaxy type having systematically more or fewer satellites than the average.

The mean and median recession velocities of the satellite-hosting galaxies are 2938 and 2543 km s⁻¹ respectively, somewhat larger than the corresponding values for the whole sample of 143 galaxies (2539 and 2217 km s⁻¹). This indicates that the dominant incompleteness is likely to be due to the smaller effective search area for the nearer systems, rather than missing faint satellites at larger distances. In any case, the recession velocity distributions of the overall and satellite-hosting samples are only marginally different, with a Kolmogorov-Smirnov test showing a 21% chance that they could be drawn from the same parent distribution.

Our R -band imaging and the catalogued recession velocities were used to determine the total luminosities of the central hosts. The mean value for the 47 satellite-hosting galaxies was $1.53 \times 10^{10} L_{\odot}$, almost identical to our adopted luminosity for the MW, thus confirming that this is a good sample for deriving satellite properties of MW-like central galaxies.

We now move to a consideration of the properties of the satellites that were detected, with the principal aim in the present paper of identifying those that can be considered similar to the LMC or SMC. A more detailed discussion of, for example, SF rates, evidence for starbursts or suppressed SF, continuum and emission-line morphologies, and the overall satellite galaxy luminosity function will be presented in a future paper (C. F. Ivory et al., in preparation).

The first satellite property to consider is projected separation, measured from the R -band centroid of the host to that of the satellite. Figure 2 shows the distribution of these values for the 62 satellites, with the dotted line corresponding to all satellites, and the solid line to just those with central galaxies more distant than 30 Mpc. The latter thus excludes those systems with significant incompleteness for outlying satellites due to the smaller projected area surveyed. The mean and median projected separations of the satellites from their central galaxies are 81 and 66 kpc respectively, rising to 98 and 90 kpc for systems beyond 30 Mpc. These are of course lower limits to the true separations since the line-of sight separation is almost completely unconstrained

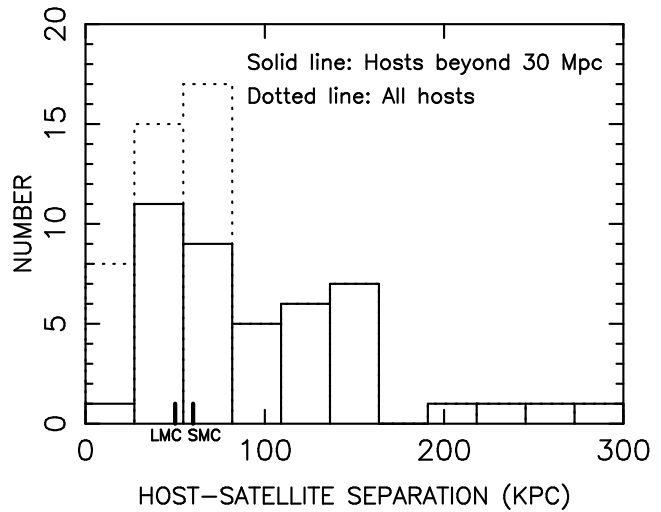


Figure 2. Histogram showing the projected separations of the satellites from the central galaxies. The dotted line is for the full sample of 62 satellites, the solid line is for the subset beyond 30 Mpc. Thus central galaxies within 30 Mpc only contribute close-in satellites, lying less than ~ 80 kpc in projected separation from their central galaxies. The two thick vertical lines show the actual separations of the MCs from the MW.

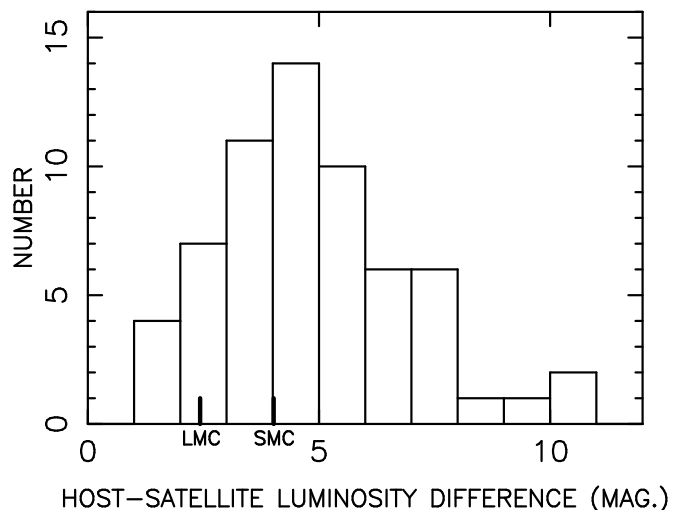


Figure 3. Histogram showing distribution of R -band magnitude differences between satellite galaxies and their central host galaxies. The two thick vertical lines mark the equivalent differences for the Magellanic Clouds, relative to the Milky Way.

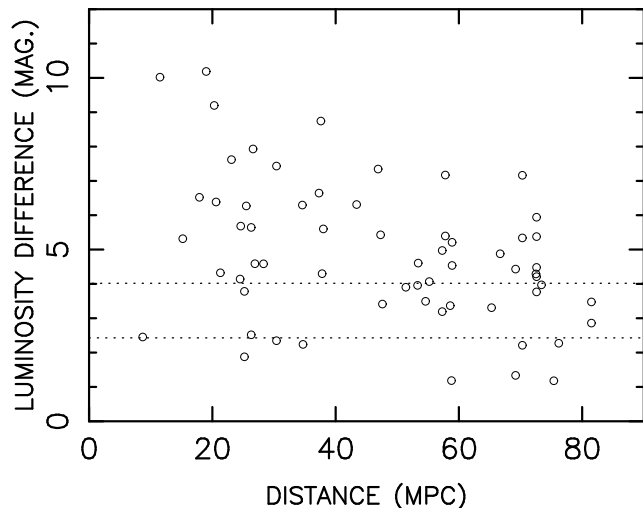


Figure 4. *R*-band magnitude differences between satellite galaxies and their central host galaxies plotted against distance in Mpc. The horizontal lines show the equivalent magnitude differences for the LMC (lower) and SMC (upper), illustrating that we are sensitive to systems with more extreme luminosity contrasts than the SMC and Milky Way to the limits of our survey.

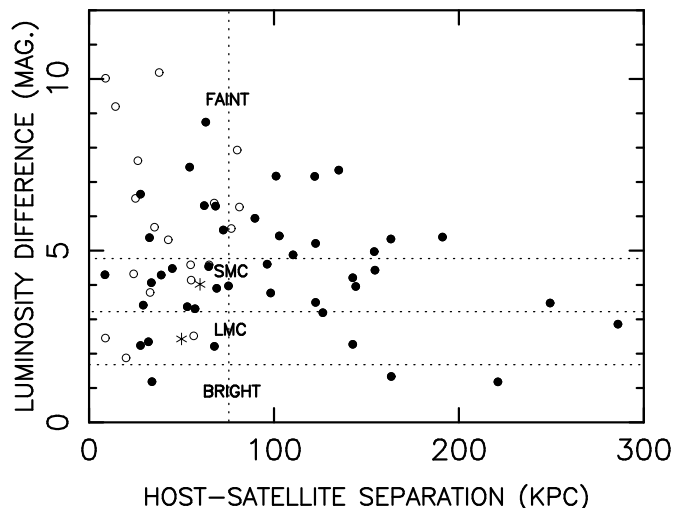


Figure 5. *R*-band magnitude differences between satellite galaxies and their central host galaxies plotted against projected separations. Open circles are for systems within 30 Mpc, filled circles lie beyond this distance, and the asterisks show the estimated values of the Magellanic Clouds (plotted at their actual distances from the Milky Way). The dashed lines separate different luminosity and projected separation classes of satellites, as defined and explained in the text.

and hence is not included in these estimates. The thick vertical lines correspond to the *actual* distances of the LMC and SMC from the MW; even without correcting for projection effects, it is clear that the MC should be considered nearby companions, although we do find other examples with comparable separations.

The next parameter considered is satellite luminosity. This is presented in Fig. 3, where we follow Zaritsky et al. (1993) in plotting the difference between the total *R*-band magnitudes of satellites and their central hosts. This quan-

tity is chosen as best representing the evolutionary importance of the satellites in terms of the dynamical impact of future mergers and their importance as sources of future gas supply. It is also a useful quantity for comparison with cosmological simulations, where luminosity ratios are more easily calculated than absolute luminosities. Again the equivalent properties are calculated for the LMC and SMC, using the numbers quoted in the Introduction, and indicated in Fig. 3 by the thick vertical lines. In terms of this relative luminosity, the MC must clearly be considered very substantial satellites, with the LMC being brighter than 54 of the 62 satellites found, and the SMC brighter than 40 of the 62. The distribution shown in Fig. 3 shows a monotonic rise towards relatively fainter satellites down to those 5 mag fainter than their central galaxies, followed by a turnover and a tail to the distribution extending to ~ 10 mag (showing that we can detect satellites with luminosities as low as 10^{-4} times that of their central galaxy). To investigate the effect of incompleteness on this turnover, in Fig. 4 the same luminosity difference parameter is plotted as a function of the distance of the galaxy system. While the very faintest satellites are only found within ~ 20 Mpc, Fig. 4 shows that satellites with a luminosity difference of ~ 7 mag are found to virtually the full depth of our sample. This is well beyond the turnover at 5 mag, implying that this turnover is likely to be real, and importantly for the present analysis shows that we are very unlikely to miss satellites as bright as either of the MCs. The distribution in Fig. 3 is fairly similar to that found by Zaritsky et al. (1993) for their sample of 69 satellites; they find the magnitude difference distribution to rise to a peak at 3 - 3.5 mag, with a tail out to ~ 7.5 mag.

Figure 5 combines the two parameters discussed above, host-satellite luminosity difference and host-satellite spatial separation, in one scatter plot that enables an overall comparison of the 62 satellites with the SMC and LMC, the latter being plotted as asterisks. The dotted lines are chosen, somewhat arbitrarily, to indicate satellites that might be considered most closely analogous to the SMC and LMC. The top and bottom horizontal lines correspond to satellites with one-half of the normalised luminosity of the SMC, and double the normalised luminosity of the LMC, respectively. The central line corresponds to both double the SMC normalised luminosity, and half the LMC luminosity (noting that within errors, the LMC is four times as bright as the SMC). Thus the horizontal lines define four luminosity difference ranges that we term ‘Bright’, ‘LMC-like’, ‘SMC-like’ and ‘Faint’, as labeled on Fig. 5. The vertical dashed line corresponds to the ‘Magellanic radius’ defined above. Some conclusions are apparent from this figure. Relative to these boundaries, three satellites are *significantly* brighter than the LMC; two of these (in the bottom right-hand box) are at substantial projected distances from their host galaxies and might better be considered as binary companions or group members. All three of these bright satellites have luminosities close to one-third that of their hosts. There are 9 satellites within a factor 2 of the normalised LMC luminosity, of which 3 are distant companions but 6 are sufficiently close in projected separation to be considered ‘MC-like’. Similarly, there are 22 satellites within a factor 2 of the normalised SMC luminosity, with 7 being distant companions and 15 ‘MC-like’. Finally, 28 of the 62 satellites are more than a factor two fainter than the SMC in normalised luminosity.

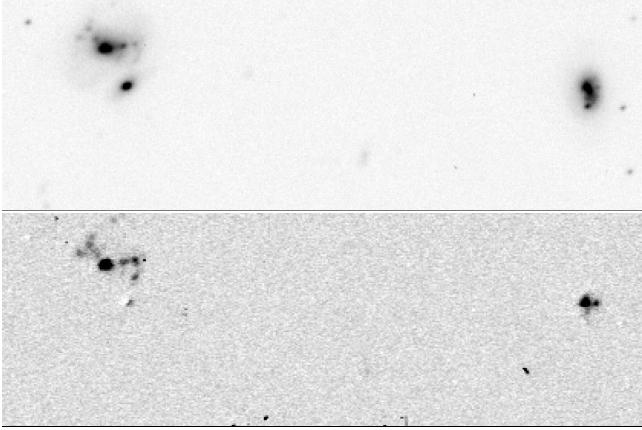


Figure 6. *R*-band (top) and $H\alpha$ (bottom) images of the two satellites of NGC 2596.

So overall, our search of 143 bright, star-forming disk galaxies has yielded 21 satellites which we consider to be similar to the MCs in terms of normalised luminosity and proximity to their central galaxies; of these, 6 most closely resemble the LMC, and 15 the SMC.

5 MULTIPLE SATELLITE SYSTEMS

One further distinctive characteristic of the MCs is their binary nature. Not only are there two of them, but they are close together in space, and they appear, from their relative velocities (Kroupa & Bastian 1997), to be a bound pair. Fujimoto et al. (1999) estimate that they are orbiting with a separation varying between ~ 5 and 30 kpc, currently ~ 22 kpc, i.e. substantially less than their separation from the MW. In this section we look at those systems from the present sample with more than one star-forming satellite, to see whether there are any other examples of such binary satellites.

There are 10 host galaxies with 2 or more satellites in the present sample. These are listed below, with details of the numbers of star-forming satellites, the radial projected separation from the host and the magnitude difference relative to the host for each satellite, and comments on any pairs of satellites that lie close to one another in projection.

UGC 2627

3 satellites found, with the following properties:
65 kpc separation/4.5 mag difference; 122 kpc separation/5.2 mag difference; 34 kpc separation/1.2 mag difference.

This galaxy has one SMC-like companion, one faint and distant companion, and one close-in and very bright companion that we classify as too bright to be considered LMC-like. The bright and SMC-like companions appear fairly close to one another, with a projected separation of 40 kpc, but do not appear to be a true pair.

NGC 1961

2 satellites found, with the following properties:
126 kpc separation/3.2 mag difference; 154 kpc separation/5.0 mag difference.

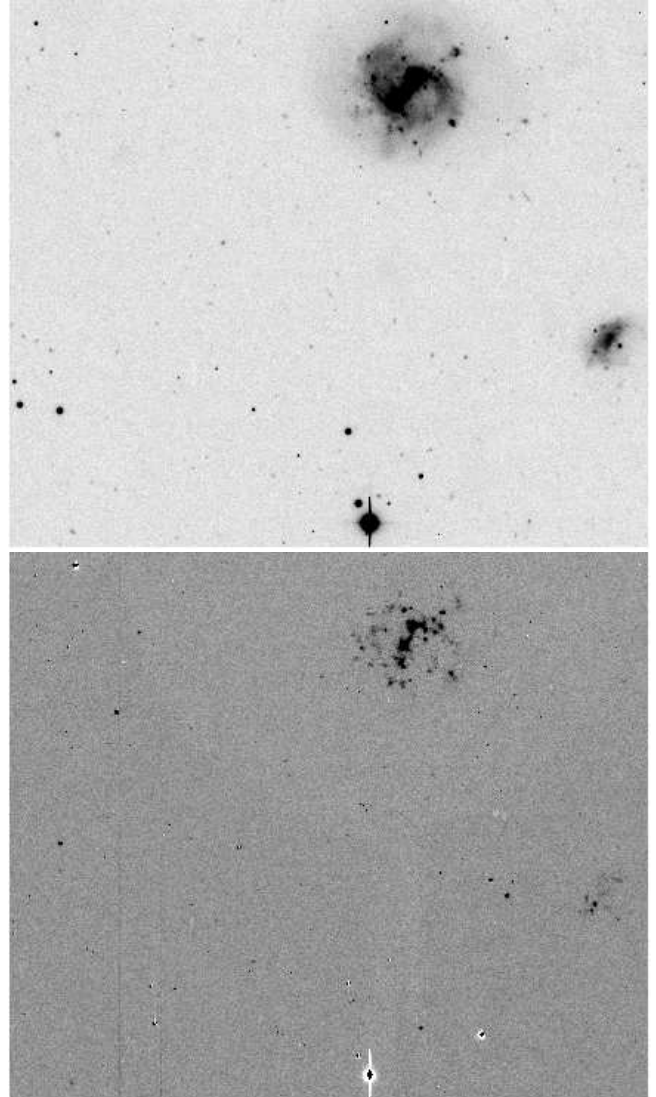


Figure 7. *R*-band (top) and $H\alpha$ (bottom) images of NGC 2604 and two satellites. The fainter satellite (barely visible in this reproduction) is in the extreme lower-left hand corner of the frames.

tion/5.0 mag difference.

The first of these satellites lies on the SMC/LMC mag difference borderline, the other is faint. Both are distant from the central galaxy, but closer to one another (42 kpc in projected separation).

UGC 4195

3 satellites found, with the following properties:
68 kpc separation/2.2 mag difference; 122 kpc separation/7.2 mag difference; 163 kpc separation/5.3 mag difference.

The first of these is a good LMC analogue, the other two are faint and distant satellites. The two faint satellites are quite close to one another, 41 kpc in projected separation.

NGC 2596

2 satellites found, with the following properties:

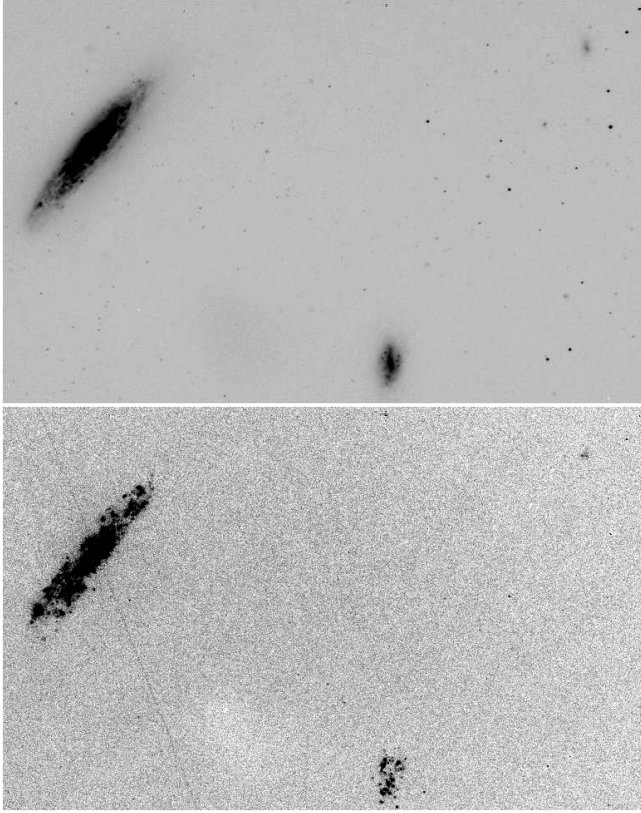


Figure 8. *R*-band (top) and $H\alpha$ (bottom) images of NGC 4666 and two satellites. The fainter satellite is in the extreme top-right hand corner of the frames.

286 kpc separation/2.9 mag difference; 249 kpc separation/3.5 mag difference.

In terms of mag difference, these satellites resemble the LMC and SMC respectively, but they are the two most distant satellites in the present sample. Interestingly, they are quite close to one another, with a projected separation of 41 kpc. *R*-band and continuum-subtracted $H\alpha$ images of the two satellites only (NGC 2596 is not shown) are presented in Fig. 6. Both satellites have clumpy $H\alpha$ emission with strong central components.

NGC 2604

2 satellites found, with the following properties:
32 kpc separation/2.3 mag difference; 54 kpc separation/7.4 mag difference.

The first of these is a good LMC analogue (with barred, irregular structure and multiple HII regions, see Fig. 7), the second is very faint but still close to the central galaxy. They do not appear to be a satellite pair, with a projected separation between the two greater than the central - satellite separations.

NGC 3074

5 satellites found, with the following properties:
33 kpc separation/5.4 mag difference; 45 kpc separation/4.5 mag difference; 98 kpc separation/3.8 mag difference; 90 kpc separation/5.9 mag difference; 143 kpc

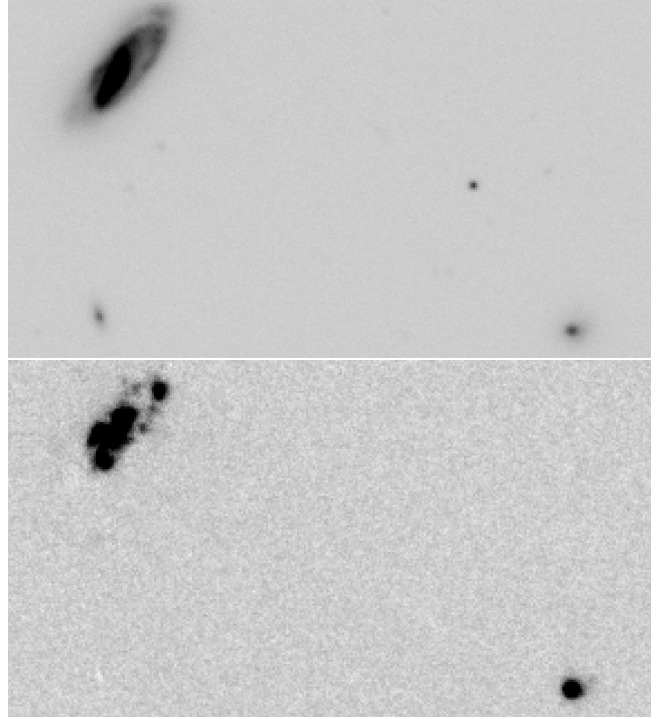


Figure 9. *R*-band (top) and $H\alpha$ (bottom) images of the two satellites of NGC 4675.

separation/4.2 mag difference.

Three of the five can be considered SMC analogues in terms of mag difference, and one of these also lies within the ‘Magellanic radius’. Of the other two, both are very faint, with one being close in and the other very distant. In terms of satellite-satellite separations, it should be noted that the two closest-in satellites (one faint, one SMC-like) are also close to one another, with a projected separation of 13 kpc. Otherwise, the satellites are widely spaced.

NGC 4666

2 satellites found, with the following properties:
57 kpc separation/2.4 mag difference; 77 kpc separation/5.6 mag difference.

The first of these is an excellent LMC analogue (see Fig. 8); as with the brighter satellite of NGC 2604, it appears barred in the red continuum image, but irregular with multiple HII regions in the $H\alpha$ image. The other satellite is very faint, and quite distant from both the central galaxy and the bright satellite.

NGC 4675

2 satellites found, with the following properties:
163 kpc separation/1.3 mag difference; 155 kpc separation/4.4 mag difference.

The first of these is a very bright satellite, the other much fainter but just an SMC-analogue in mag difference; both are very distant from the central galaxy, but do lie close to one another, 23 kpc in projected separation. Figure 9 shows just the two satellites, not NGC 4675; the brighter

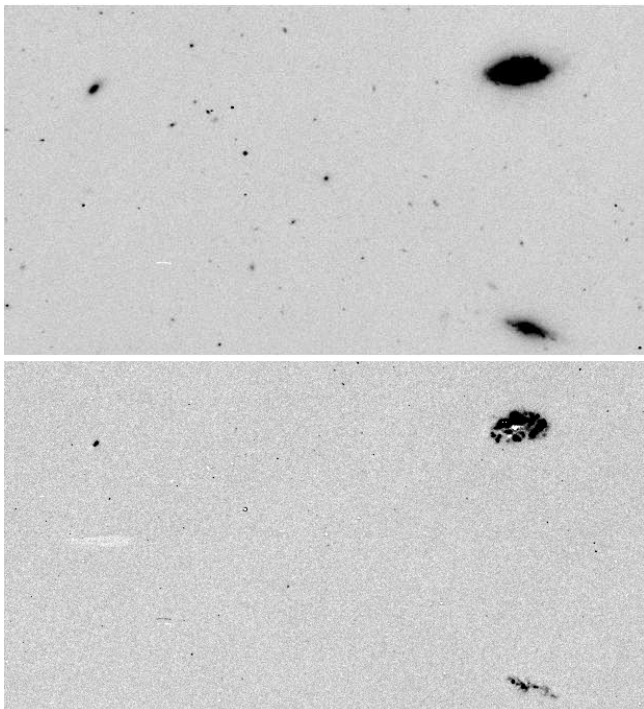


Figure 10. *R*-band (top) and $H\alpha$ (bottom) images of NGC 5303 and two satellites. The fainter satellite is toward the top-left hand corner of the frames.

of the two appears to be a disturbed barred spiral galaxy, consistent with the classification of it as being too bright to be comparable with the MC. The fainter satellite shows very intense, centrally concentrated $H\alpha$ emission.

NGC 4708

2 satellites found, with the following properties:
101 kpc separation/7.2 mag difference; 191 kpc separation/5.4 mag difference.

Both are very faint and distant satellites, which are also well separated from one another (152 kpc).

NGC 5303

2 satellites found, with the following properties:
20 kpc separation/1.87 mag difference; 33 kpc separation/3.78 mag difference.

Individually these are good LMC and SMC analogues in mag difference and proximity to their host. However, they do not appear to be a satellite pair, with a larger satellite-satellite separation (39 kpc) than the host-satellite separations. Morphologically, the brighter satellite appears to be an edge-on disk, possibly with a bulge, while the potentially ‘SMC-like’ satellite has a cometary appearance in red continuum and a single compact region of $H\alpha$ emission (see Fig. 10).

Overall we find 5 cases of pairs of satellites that are significantly closer to one another than they are to their central galaxy. Three of these pairs have projected separations of 41 - 42 kpc, substantially greater than the current LMC - SMC distance. The closest pair, at 13 kpc projected separation, are the two innermost satellites of NGC 3074.

Probably the best candidates for a bound pair are the two objects associated with NGC 4675 (shown in Fig. 9), with a projected separation of only 23 kpc, while the mean distance from the pair to the central galaxy is almost 7 times as large. One question regarding this putative pair is whether they might be regarded as a central-satellite system in their own right, given that the brighter galaxy of the pair is one of the 3 ‘very bright’ satellites, substantially more luminous than the LMC.

6 DISCUSSION

To the best of our knowledge, the only previous search specifically for star-forming satellites that has been reported in the literature is our own study using the $H\alpha$ GS data, James et al. (2008c). Given that identical methods were used, it is not surprising that the present study confirms the main result of James et al. (2008c); the large majority of central galaxies do not host star-forming satellites. This conclusion is unlikely to be changed by the levels of incompleteness identified in section 3.2 above. The present study does, however, find larger numbers of satellites per central galaxy searched than the ratio of 1 satellite per 13 central galaxies found by James et al. (2008c); this may be largely to do with the higher typical luminosities of the central galaxies surveyed in the present study. To summarise our numbers for comparison with other studies, Fig. 5 shows 1 bright, 6 LMC-like, 15 SMC-like and 15 faint satellites within the ‘Magellanic radius’, from a total sample of 143 central galaxies searched. To correct for incompleteness in the searched volume, these observed numbers should be multiplied by 1.35. Extending this to all galactocentric radii, Fig. 5 shows 3 bright, 9 LMC-like, 22 SMC-like and 28 faint satellites, which should be multiplied by 1.96 to correct for volume incompleteness.

Holmberg (1969) searched for satellites around 174 galaxies out to a galactocentric radius of ~ 57 kpc (after correction to $H_0=70$). He found 274 ‘physical’ companions (i.e. after a statistical background subtraction). For a subset of 53 central galaxies at Galactic latitude $>30^\circ$, he found 82 such companions with a visual absolute magnitude estimated to be brighter than -15.3 . This corresponds approximately to our SMC-like limit, and within this radius we find only 11 star-forming satellites, at least an order of magnitude fewer than the total satellite numbers inferred by Holmberg (1969). Similarly, Lorrimer et al. (1994) find 1 satellite brighter than $M_B=-16.5$ (corresponding to a luminosity of $6.2 \times 10^8 L_\odot$, somewhat brighter than the SMC) per central galaxy. We find only 15 satellites this bright in our sample, or 29 after correction for volume incompleteness, still only 1 star-forming satellite per 5 central galaxies searched. Our low numbers compared with both Holmberg (1969) and Lorrimer et al. (1994) may imply efficient truncation of SF in satellites, such that the majority of satellites become red, quiescent systems well before they merge with their central galaxies, or there may be some remaining inclusion of line-of-sight projected companions in the earlier studies.

It is also of interest to compare with Zaritsky et al. (1993), who searched 45 central galaxies of types Sb - Sc, with absolute magnitudes M_B -19.5 to -20.5 . They found

69 satellites, with a distribution of relative luminosities that is generally consistent with that of the present sample (see Section 4), and concluded that close-in satellites have marginally smaller sizes than those at large galactocentric distance. There is some evidence for a similar effect in Fig. 5, in the sense that the faintest satellites seem to be preferentially close-in, with the upper right-hand corner of the plot being underpopulated.

Many satellite studies have made use of the SDSS, exploiting the huge numbers of galaxies and the immense statistical weight this provides. However, it should be noted that the SDSS studies explore an almost completely distinct part of parameter space from the present work, in particular with regard to the luminosity of satellites found. For example, Ann et al. (2008) studied a sample of 2254 central galaxies from SDSS Data Release 5, with mean luminosities close to L_* and thus very comparable to the present sample. They found 4986 companions associated with these galaxies, and studied the effects of central galaxy type and proximity on the properties (early- vs. late-type) of the companions. However, it is important to note that these companions have a median luminosity difference of only 1.8 mag relative to their central galaxies. Our study finds much fainter satellite galaxies, with almost half being less than 1% of the luminosity of their central galaxy.

We now turn to a comparison with theoretical studies, and in particular with the recent predictions from Λ CDM models. The main point to make here is that the MW appears unusual in the possession of bright, star-forming satellites, and thus the prediction of such satellites (Libeskind et al. 2007) should not be taken as validation of models. Thus the modifications to models suggested by Simon & Geha (2007), Koposov et al. (2009) and Kravtsov (2010) to produce the full range of MW satellites including the MC are not required in order to explain the satellite properties of the ensemble of bright disk galaxies studied here. More positively, the finding of Benson et al. (2002) (reproduced in the ‘baseline’ versions of many subsequent simulations), that fewer than 5% of disk galaxies have satellites resembling the LMC, is consistent with our results.

This scarcity of satellites found here argues against such systems as a dominant source of gas supply at the current epoch. Most central galaxies have no gas-rich satellites within the volumes surveyed here. If such satellites are present but typically outside the surveyed volume, this would put them at galactocentric distances greater than ~ 200 kpc. The typical dynamical friction timescales would then be at least several Gyr (Boylan-Kolchin, Ma, & Quataert 2008; Taffoni et al. 2003), clearly too long for substantial gas supply for a large spiral, which requires the gas content of a Magellanic-type satellite every Gyr or so. Fainter satellites have even longer dynamical timescales and so seem unlikely to provide a significant contribution to the gas supply, even if there is a strong upturn in numbers faintward of our detection limits.

We repeat the major caveat on the present work, which is that this technique is completely insensitive to gas-poor red-sequence satellites. A survey of satellite galaxies of all types (M. Prescott et al. in preparation) is currently being prepared from the Galaxy And Mass Assembly (GAMA) project (Driver et al. 2009; Baldry et al. 2010), using the AAOmega spectrometer on the Anglo-Australian Telescope,

and will provide a useful complementary view of satellite populations.

This work has provided a number of satellites which can be used to compare the detailed properties of the LMC and SMC, with several examples of analogues for each. The one aspect of the Clouds for which there is no clear analogue is their binary nature, with all of the possible satellite pairs being either significantly more widely separated than the MC, or very close to the central galaxy. This is an interesting discovery in itself, but is also somewhat disappointing, as there are important questions on the role of binarity in forming the Magellanic Stream, which could have been clarified by observing more such examples.

7 CONCLUSIONS

Our main conclusions are as follows. Magellanic-type satellite galaxies are rare; for the majority (approximately two-thirds) of the central galaxies searched, no star-forming satellites at all have been found. Among those SF satellites that are found, the MC are significantly brighter than the average, closer to their central galaxy than most, and are also unusual in that they form a close pair. We caution against using the MW and its immediate environment as a model for simulations of galaxy formation, particularly as regards bright satellites. However, some recent models that are not tuned to produce MC-like satellites do accurately predict the bright satellite fractions found in the present study. Our results also highlight substantial problems with gas-rich satellites as the major source of gas supply to maintain SF in disk galaxies. The major caveat on this work is that it applies to star-forming satellites only, so studies of the red satellite fraction, e.g. from the GAMA survey, are essential to provide a full picture of the satellite population.

The next paper in this series will provide a full catalogue of satellite properties, including the 62 discussed here, resulting from a larger and more eclectic sample of $H\alpha$ imaging, including R -band and $H\alpha$ luminosity functions, stellar masses, SF rates, and the effects of central galaxy proximity on SF properties.

ACKNOWLEDGMENTS

This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration. The Isaac Newton Telescope is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. PAJ and CFI are happy to acknowledge the UK Science and Technology Facilities Council for research grant and research studentship support, respectively. We thank Sue Percival for useful comments on a draft of this paper, and the referee, Hong Bae Ann, for a positive and helpful report.

REFERENCES

Anderson J. P., James P. A., 2008, MNRAS, 390, 1527

- Ann H. B., Park C., Choi Y., 2008, MNRAS, 389, 86
- Appleton P. N., et al., 2006, ApJ, 639, L51
- Baldry I. K., et al., 2010, MNRAS, 404, 86
- Benson A. J., Frenk C. S., Lacey C. G., Baugh C. M., Cole S., 2002, MNRAS, 333, 177
- Boylan-Kolchin M., Ma C.-P., Quataert E., 2008, MNRAS, 383, 93
- Boylan-Kolchin M., Springel V., White S. D. M., Jenkins A., 2009, 398, 1150
- Casuso E., Beckman J. E., 2004, A&A, 419, 181
- Cluver M. E., et al., 2010, ApJ, 710, 248
- Domínguez-Palmero L., Balcells M., 2008, A&A, 489, 1003
- Driver S. P., et al., 2009, A&G, 50, 12
- Fujimoto M., Sawa T., Kumai Y., 1999, in J. E. Barnes & D. B. Sanders ed., *Galaxy Interactions at Low and High Redshift Vol. 186 of IAU Symposium, The Magellanic Stream and the Magellanic Cloud System.* pp 31–+
- Grcevich J., Putman M. E., 2009, ApJ, 696, 385
- Helmboldt J. F., Walterbos R. A. M., Bothun G. D., O’Neil K., de Blok W. J. G., 2004, ApJ, 613, 914
- Holmberg E., 1969, Arkiv for Astronomi, 5, 305
- Hopkins P. F., Hernquist L., Cox T. J., Younger J. D., Besla G., 2008, ApJ, 688, 757
- Ivory C. F., James P. A., 2010, arXiv, arXiv:1009.2394
- James P. A., Knapen J. H., Shane N. S., Baldry I. K., de Jong R. S., 2008a, A&A, 482, 507
- James P. A., O’Neill J., Shane N. S., 2008c, A&A, 486, 131
- James P. A., Prescott M., Baldry I. K., 2008b, A&A, 484, 703
- James P. A., et al., 2004, A&A, 414, 23
- Kennicutt Jr. R. C., Hodge P. W., 1986, ApJ, 306, 130
- Klypin A., Kravtsov A. V., Valenzuela O., Prada F., 1999, ApJ, 522, 82
- Koposov S., et al., 2007, ApJ, 669, 337
- Koposov S. E., Yoo J., Rix H., Weinberg D. H., Macciò A. V., Escudé J. M., 2009, ApJ, 696, 2179
- Kravtsov A., 2010, *Advances in Astronomy*, 2010, 8
- Kroupa P., Bastian U., 1997, *New Astronomy*, 2, 77
- Larson R. B., Tinsley B. M., Caldwell C. N., 1980, ApJ, 237, 692
- Libeskind N. I., Cole S., Frenk C. S., Okamoto T., Jenkins A., 2007, MNRAS, 374, 16
- Lorrimer S. J., Frenk C. S., Smith R. M., White S. D. M., Zaritsky D., 1994, MNRAS, 269, 696
- Martínez-Delgado D., Peñarrubia J., Gabany R. J., Trujillo I., Majewski S. R., Pohlen M., 2008, ApJ, 689, 184
- Meurer G. R., et al., 2006, ApJS, 165, 307
- Moore B., Ghigna S., Governato F., Lake G., Quinn T., Stadel J., Tozzi P., 1999, ApJ, 524, L19
- Okamoto T., Frenk C. S., Jenkins A., Theuns T., 2010, MNRAS, 406, 208
- Simon J. D., Geha M., 2007, ApJ, 670, 313
- Taffoni G., Mayer L., Colpi M., Governato F., 2003, MNRAS, 341, 434
- Walsh S. M., Jerjen H., Willman B., 2007, ApJ, 662, L83
- Willman B., et al., 2005, ApJ, 626, L85
- Zaritsky D., Smith R., Frenk C., White S. D. M., 1993, ApJ, 405, 464
- Zavala J., Okamoto T., Frenk C. S., 2008, MNRAS, 387, 364